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Physico-Mechanical and Acoustic Characterization of *Mimusops andongensis* Wood from Benin in West Africa

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Abstract: Wood is a multifunctional anisotropic biomaterial. It is used in various fields, including the craft industry and the construction of structural works. In heavy construction or in wetlands, species with high technological characteristics are sought after. *Mimusops andongensis* is a species empirically identified as having good technological properties. However, none of these reference characteristics are known. Thus, to fill this gap, we tested 500 mm × 20 mm × 20 mm prismatic specimens of *Mimusops andongensis* wood using CIRAD-Forest's acoustic BING (Beam Identification by Non-destructive Grading) method to determine density ρ, Young's modulus E and shear modulus G, internal friction tanδ and then evaluated the specific stiffness modulus E/ρ. On other 20 mm side cubic specimens, we evaluated the physical properties. From this investigation, *Mimusops andongensis* timber is a heavy to very heavy timber with high modulus. Its volume shrinkage is moderate with low tangential and medium radial shrinkage. Its low shrinkage anisotropy predicts low distortional and splitting deformation. Its specific stiffness is high on the order of (18 ± 1) GPa for a low internal friction of $(0.64 \pm 0.15) \times 10^{-2}$. In a humid environment, the loss of mechanical properties, by increasing its moisture content, even by 20 %, leaves *Mimusops andongensis* timber in the range of woods with very appreciable properties. Referring to the highly valued species, it can be used in works both in structure and acoustics.

Key words: Infra-density · Heartwood · Tropical Hardwood · Compression · Bending · Moisture Content

INTRODUCTION

Trees have a multifunctional role and wood from them is a highly valued material. In the implementation of projects for the construction of tourist structures on stilts, wood species with high technological characteristics are sought. Among these species identified, we can mention *Mimusops andongensis*.

The genus Mimusops belongs to the class Magnoliopsida, order Ebenales/Ericales and to the family Sapotaceae. *Mimusops andongensis* Hiern is a Wild Edible Fruit Tree (WFET) listed among food and medicinal species. It represents a multiple-use species for local populations [1-4]. This predisposes it to a potential threat. Studies conducted in Benin, following the criteria of the International Union for Conservation of Nature (IUCN), have classified *Mimusops andongensis* Hiern as a rare and threatened species in Benin [5-8]. The rarity of this species has certainly resulted in its non-description in the analytical flora of Benin while *Mimusops kummel* is well presented [9].

In national languages, *Mimusops andongensis* Hiern is called bohê [10] or afoutin in Fon [11] and égui ochéé in Holli [10], for others in Fon it is called kinwi and in

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Nagot igui odu or ochèdo. *Mimusops andongensis* and *Mimusops kummel* are found in semi-deciduous forests and riparian forests which represent their natural habitat [5, 12]. *Mimusops andongensis* and *Mimusops kummel* also occur from north to south of Benin along three bioclimatic zones [13]. Hounkpèvi *et al*. studying the structure and ecology of two other species (*Diospyros mespiliformis* Hochst. ex A. DC. and *Dialium guineense* Willd) from the Massi Reserve in Lama, noted among others the presence of *Mimusops andongensis* with high heights [14]. *Mimusops andongensis* is a small to medium sized shrub or tree up to 20 m tall, containing latex. It has a dense, heavily branched crown [15]. The bole can measure up to 100 cm in diameter but usually much less. In southern Benin, *Mimusops andongensis* is locally quite common in periodically flooded forests on heavy clay soils, where it represents about 3 % of the trees [15]. *Mimusops andongensis* wood is a hardwood used in forestry and for fishing. It is locally highly valued in both Benin and Nigeria [15]. It is used in construction, in dugout canoes, axe handles and carving, charcoal production and as fuel wood [11, 16, 17]. The bark, roots, leaves and latex from the bark are exploited to treat malaria, toothache, skin infections and as a penile stimulant, etc [1, 17-19]. The latex of *Mimusops andongensis* is still used to flavour palm wine. The fruit is used as a substitute for chewing gum [15]. *Mimusops andongensis* is a species known to have magical powers [1, 20] and is one of the potential commercial species in the Central Nucleus of the Lama Forest under ONAB management [21]. Sinasson *et al.* [11] determined the uses, local knowledge and abundance mutations of Mimusops species in Benin. Sinasson *et al.* [13] also investigated ecological patterns and the effectiveness of protected areas in preserving habitats for Mimusops species under climate change. Similarly, Sinasson *et al.* [22] evaluated the structure, stability and plant morphology of *Mimusops andongensis* and *Mimusops kummel* under different socio-ecological constraints in Benin. Unfortunately, all these studies on *Mimusops andongensis* did not address the technology of its wood. That is why, in our logic to have a good data base on the technological characteristics of the woods exploited in Benin, the wood of *Mimusops andongensis* was the subject of physical, mechanical and acoustic characterization tests.

The objective of this study was therefore to evaluate the physical-mechanical and acoustic characteristics of *Mimusops andongensis* wood from Benin. The properties obtained are compared with those of other highly prized species in order to deduce the possible uses of *Mimusops andongensis* wood. Finally, the influence of humidity on the characteristics of *Mimusops andongensis* wood was studied.

The main characteristics determined are density, infra-density, volume shrinkage, radial shrinkage, tangential shrinkage, modulus of elasticity in compression, modulus of elasticity in bending, shear modulus, internal friction and specific rigidity.

MATERIALS AND METHODS

For the investigation, we used, the plant material consisted of *Mimusops andongensis* specimens cut from a foot taken at plot 22a of Massi forest. This forest is under ONAB (National Timber Office of Benin) management in Lama in southern Benin. Plot 22a is at the edge of the central core. The tree is apparently young with a diameter of about 32 cm at man's height. The prohibitions on the species have not allowed more trees to be harvested. The wood is very poorly hardened with a heartwood percentage of about 48 %. Figure 1 shows the trunk and a log of the *Mimusops andongensis* tree. From this trunk, in addition to the 2×2×50 cm prismatic specimens (Figure 2) cut for mechanical measurements, 2 cm edge cubic specimens were also cut for evaluation of physical parameters (density and shrinkage).

For the mechanical measurements, the method of mechanical characterization used is the non-destructive one based on the BING device (Beam Identification By Non-Destructive Grading) of CIRAD-Forêt whose principle was the subject of work of Brancheriau [23]. The device is based on the theory of beams and is based on the Bernoulli and Timoshenko models. It uses frequency analysis of vibration signals by Fast Fourier Transform (FFT) and has been used in the work of Ahmed and Adamopoulos [24] and Hounlonon *et al.* [25]. BING is used to obtain the longitudinal flexural and compressive modulus of elasticity, shear modulus, internal friction and specific stiffness, among others.

The determination of physical parameters such as shrinkage, density and infra-density or basal density were done according to the AFNOR standard as described by the *Memento du Forestier* [26], Gérard *et al.* [27], Kouchadé *et al.* [28] and Tonouéwa *et al.* [29, 30]. The tests were performed on standardized specimens without defects. The cubic specimens sized for the physical tests were immersed in water until fully saturated.

(a) (b) (c)

Fig. 1: Trunk (a), washer (b) and top view (c) of *Mimusops andongensis* trunk shaped for debitage joinery

Fig. 2: Some specimens of *Mimusops andongensis* wood

At saturation, the following measurements were taken on each specimen: the saturated volume by the buoyancy method, the radial, tangential, axial or longitudinal dimensions using an electronic caliper of 0.0 1mm precision. The specimens were then stabilized in a temperature-controlled oven at 103°C. At the end of each stabilization and at the end of the drying process, the anhydrous mass, also called dry mass, was measured using a 0.01 g precision electronic balance. Also, the dimensions in the orthotopic directions of each sample were measured.

The data obtained from BING or by calculation allowed us to obtain the descriptive statistics results presented in Table 1.

Table 1: Physical, mechanical and acoustic properties of *Mimusops andongensis*

Air-dry density (kg.m^{-3})	*m*	1, 017
	e	58
Anhydrous density (kg.m^{-3})	*m*	948
	e	47
Infra-density (kg.m^{-3})	*m*	854
	e	62
Total volume shrinkage (%)	*m*	10.01
	e	2.43
Tangential shrinkage R_T (%)	*m*	6.35
	e	1.79
Radial shrinkage R_R (%)	*m*	4.16
	e	0.94
Shrinkage anisotropy R_T/R_R	*m*	1.53
	e	0.25
Modulus of elasticity in bending (MPa)	*m*	18, 470
	e	1, 828
Modulus of elasticity in compression (MPa)	*m*	16, 749
	e	1, 250
Shear modulus (MPa)	*m*	1, 323
	e	255
Specific modulus of elasticity (GPa or MPa.kg^{-1}.m^3)	*m*	18
	e	1
Internal friction tanδ (10^{-2})	*m*	0.64
	e	0.15

m: mean e: standard deviation

RESULTS

Physical, Mechanical and Acoustic Properties of *Mimusops andongensis*: The tests carried out on 20 samples allowed to determine the average values and standard deviations of the physical and mechanical parameters presented in Table 1. Thus, the wood of *Mimusops andongensis has an* air-dry density of (1,017 ± 58) kg.m^{-3}, an anhydrous density of (948 ± 47) kg.m^{-3} and an infra-density of (854 ± 62) kg.m^{-3}. Regarding shrinkage, *Mimusops andongensis* has average volume shrinkage of less than 13 %. The tangential shrinkage of (6.35 ± 1.79) % is relatively low as well as the radial shrinkage which is (4.16 ± 0.94) %. The shrinkage anisotropy remains low and is (1.53 ± 0.25). Thus, in terms of mechanical stiffness, *Mimusops andongensis* has longitudinal flexural (18470 ± 1,828) MPa and compressive (16,749 ± 1,250) MPa moduli. Its specific stiffness is (18 ± 1) GPa. Its shear modulus is (1,323 ± 255) MPa. They are, as well as its internal friction, in the order of those of tropical hardwoods. Its degree of dissipation of vibrational energy by internal friction) that is internal friction tanδ is very low and less than 10^{-2}.

DISCUSSION

Mimusops Andongensis Wood Compared to Woods of High Technological Value in Benin: From our research in the literature, the physical-mechanical and acoustic properties of *Mimusops andongensis* have not been studied.

Mimusops andongensis is a heavy wood, even very heavy. Cross-referencing our results with the characteristics of other species, the density of *Mimusops andongensis* remains far better than that of highly prized species such as *Tectona grandis* (800 kg.m^{-3}, [31]), *Acacia auriculiformis* (825 kg.m^{-3}, [25]), *Afzelia africana* (800 kg.m^{-3}, [32]), *Diospyros mespiliformis* (900 kg.m^{-3}, [32]) and *Erythropleum ivorensis (*910 kg.m^{-3}, [32]), which have a relatively high density

Investigation on timber species highly valued in North Benin such as *Anogeissus leiocarpus* and *Pseudocedrela kotschyi* showed that their infra-densities are respectively 911.0 and 824.86 kg.m^{-3} [29] and similar to that of *Mimusops andongensis*. Compared to other popular species in Benin, *Mimusops andongensis* is noble as its infra-density is much higher than that of other species such as *Afzelia africana, Pterocarpus erinaceus, Khaya senegalensis, Milicia excelsa, Gmelina arborea, Diospyros mespiliformis, Tectona grandis, Isoberlinia doka,* whose infra-densities range from 560.29 to 795.02 kg.m^{-3} [29]. The infra-density of *Mimusops andongensis* is largely above those of *Acacia auriculiformis* which has values between 496 and 705 kg.m^{-3} [30].

According to wood construction professionals, some wood species are very appreciating in heavy construction, especially in contact with the ground or water. Among these species, there are *Diospyros mespiliformis* (African Ebony), *Anogeissus leiocarpus, Erythropleum ivorensis* (Tali), *Manilkara multinervis* and *Cylicodiscus gabunensis,* ... Regardless of the density of their wood, Beninese foresters have noted the use of *Manilkara spp.* for the construction of piles in pile dwellings; of *Mimusops andongensis* for the construction of huts or straw huts in humid environments, even in contact with the ground.

Tali, a substitute for *Lophira alata* (Azobé) is a species used for constructions in humid environments or in contact with the ground [32]. It is found, in hydraulic works, heavy carpentry, bridges, heavy or industrial flooring, sleepers, posts [32].

Of use class 4 like Tali, ebony wood is used in guitar making [33], in tablet making, instrument making, luxury cabinet making, carving, turned items, wind instruments and as a resilient wood in tool handles [32].

Manilkara spp is a heavy wood with good natural durability that can be used in structural works such as musical instrument making, exterior construction, sleepers, flooring (heavy floor construction), boat building and marine works [34-37]. It is used intuitively or empirically by the inhabitants of lake villages in Benin as piles for pile constructions.

Anogeissus leiocarpus is one of the most exported wood species from Benin [38]. It is a very useful timber in works both in structure and floor construction as well as heavy works [29, 39, 40].

With a use class of 5, *Cylicodiscus gabunensis* is a wood species used in construction in Benin [41] and can also be in hydraulic works in maritime environment, in sculpture, in heavy carpentry, as crossbeam, in bridge construction, as posts, parquet, floor or in the confection of turned articles [32]. In Korea, it is used for heavy-duty flooring such as factories and warehouses, for decking and wooden floors [42]. *Cylicodiscus gabunensis* is a moderately stable to low stable wood species [32, 34].

Table 2 presents some properties of these wood species with high technological potential for high-stress structures. From the data of this table crossed with our parameters found, *Mimusops andongensis* is a valuable wood species. Thus, in terms of mechanical stiffness, *Mimusops andongensis* has high longitudinal moduli of elasticity in bending and compression as predicted by its density. Its shear modulus is moderately high. According to the reference of Gerard *et al*. [27, 32], the high modulus wood of *Mimusops andongensis* is in the range of Tali wood which has a longitudinal modulus of elasticity of 19, 490 MPa [32] and wood species of *Anogeissus leiocarpus, Diospyros mespiliformis, Cylicodiscus gabunensis, Manilkara spp* (Table 2). *Mimusops andongensis* has a lower internal friction (tanδ) than African ebony used in

Table 2: Physico-mechanical properties of some popular species according to the literature

	Authors	*Anogeissus leiocarpus*	*Diospyros mespiliformis*	*Cylicodiscus gabunensis*	*Manilkara* spp.
Density (kg.m^{-3})	[39]	1, 150 ± 50			
	[40]	1, 150			
	[32]		900 ± 60	910 ± 100	
	[41]			1, 100	
	[34]			950	
	[42]			Sapwood (770-890)	
				Heartwood (1, 160-1,230)	
	[37]				870-950
	[36]				1, 058-1, 140
	[45]				900-1, 150
Modulus of elasticity (MPa)	[39]	17, 512 ± 8, 009			
	[40]	10, 117			
	[32]		15, 500 ± 3500	22,260 ± 3,348	
	[33]		17, 680-23, 9200		
	[34]			16, 600	
	[37]				10, 800-19, 600
	[36]				16, 758-25, 650
	[35]				17, 271 ± 2253
Tangential shrinkage (%)	[29]	6.57 ± 0.14	6.59 ± 0.128		
	[32]		11.0 ± 0.5	7.9 ± 1.0	
Radial shrinkage (%)	[29]	6.18 ± 0.12	4.77 ± 0.136		
	[32]		7.0 ± 0.2	5.8 ± 0.6	
Shrinkage anisotropy	[29]	1.26 ± 0.04			
	[32]		1.6	1.4	
Volume shrinkage (%)	[29]	14.71 ± 0.25	11.39 ± 0.271		
	[39]	9.17 ± 3.64			

both construction and instrument making [32, 33]. *Mimusops andongensis* has good specific stiffness better than African ebony but lower than Tali. African Ebony wood with its specific stiffness of 17 GPa and internal friction of 0.81 10^{-2}, Tali with its specific stiffness of about 21 GPa and internal friction of 0.97 10^{-2} [32] remain more dissipative of vibrational energy by internal friction than *Mimusops andongensis* wood.

Dimensional changes below the fibers saturation point FSP affect the stability of wood products [43]. Shrinkage anisotropy is a major determinant of wood quality. Too high a value of this variable can lead to distortion or splitting [44]. The shrinkage anisotropy of *Mimusops andongensis* of 1.53 is lower than those of class 4 species such as Tali and African ebony which have anisotropy of 1.6. The propensity for deformation (distortion or splitting) of *Mimusops andongensis* is low. Volume shrinkage of *Diospyros mespiliformis* (Table 2) and *Erythrophleum ivorensis* (Tali) whose transverse linear shrinkage are R_T (8.4 ±1.2) %; R_R (5.1 ± 1.4) % [32] have higher shrinkage coefficients than *Mimusops andongensis*. *Mimusops andongensis*, due to its shrinkage anisotropy, will deform less than Tali but slightly more than *Anogeissus leiocarpus* from Benin and almost in the same range as African Ebony and *Cylicodiscus gabunensis*.

Possible Uses of *Mimusops andongensis*: Since the values of the different properties of a wood species depend on age, ecology or heredity [32, 46], it is certain that there are woods of *Mimusops andongensis* with better characteristics than the one in this study. As it is and taking into account the good technological properties of *Mimusops andongensis* similar in some cases and better in others to those of the previously mentioned species, its wood would have broadly similar applications. Its character as a heavy wood having been proven, its use in forestry and for fishing, construction, in dugouts, axe handles and carving, charcoal production and as energy wood [11, 16, 17] is well confirmed. The good values of the characteristics obtained compared to those of highly valued species such as teak, African ebony, veneer and iroko and species with high technological value, above, sufficiently prove its very good potential to be used in heavy and light constructions as noted by Lemmens who reports its use in construction [15]. It is, at the present stage, very likely to be used in structural works as the highly prized species and species of class of use 4 or 5. The distortion and splitting of this wood is less than that of Tali, but almost of the same range as African Ebony and *Cylicodiscus gabunensis*. However, its wood warps slightly more than *Anogeissus leiocarpus* from Benin.

Its dark pink to red colored texture, high density and modulus, good specific rigidity and low damping coefficient also suggest it to be a good resonance wood in instrument making or in auditorium and concert hall construction [47]. Its overall medium shrinkage and low shrinkage anisotropy reassures that it has good potential for use in various sculptures and construction in high moisture gradient environments.

But what is the influence of humidity on the characteristics of its wood and what are the great opportunities of its real use?

The Influence of Moisture on the Physical, Mechanical and Vibratory Properties of Wood: As *Mimusops andongensis is* already used in traditional structures in contact with the ground or water or on piles in a humid environment, it is useful to study the effect of water on its physical-mechanical parameters. Indeed, humidity can generate transient or permanent modifications of the properties of the wood material. Moisture variation can generate transient gradients in water content that with the wood piece will induce internal stresses [48].

The density of wood has a positive influence on the shear strength of tropical hardwoods [49] and on other mechanical properties such as modulus of elasticity [23]. The increase in moisture content leads to a decrease in specific density and mechanical properties [50]. All mechanical properties of wood grow with decreasing moisture content below the fiber saturation point (FSP) approximately at 30 % moisture content [51- 53]. The modulus of elasticity decreases with relative humidity and the modulus of rupture reache a maximum at 54.3 % RH or 8 - 9 % moisture content and then decreases with relative humidity thereafter [54]. The overall decreasing trend observed for the elastic modulus was also obtained by Gerhards [51]. Obataya *et al*. [50] reported on Sitka spruce (*Picea sitchensis*) wood that the modulus of elasticity drops overall with increasing moisture content and the loss of modulus of elasticity can be about 20 % between 0 and 30 % moisture content and about 15 % between 12 % and 30 % moisture content. Microscopic study of microfibrils, vessels and cells of wood of the same species confirmed the above dual trends for several quantities: specific gravity, modulus of elasticity and shear modulus have the same trends and internal friction an opposite trend [50]. According to the same study, from 9.6 % of moisture content onwards, an overall decreasing trend is observed for the modulus of elasticity and the shear modulus.

Also, for the vibrational properties of wood, a decreasing trend in specific stiffness E/ρ and a growth in internal friction $\tan\delta$ are observed as the equilibrium water content increases [50]. However, the degree of influence of moisture content differs in the orthotopic directions (L, R, T) of the wood [55]. There are values of water content for which the internal friction is minimal [50, 53]. Outside of this minimum, internal friction increases as the moisture content drops to zero or above the fiber saturation point [53]. The moisture content for which internal friction is minimal varies with temperature [53]. The higher the temperature, the more minimal the water content value and tends to zero [53]. Obataya *et al.* [50] also noted that internal friction increases from 0 to 1 % moisture content, decreases from 1 to 6 % moisture content and then increases again from 6 to 30 % moisture content. For the last phase of growth, the internal friction varies from $5.5\ 10^{-3}$ to about $9.7\ 10^{-3}$ or about 75 %. According to the same authors, on the basis of a microscopic study of the cells, fibrils and vessels of *Picea sitchensis* wood, the internal friction increases as the moisture content of the wood increases from 9.6 % moisture content.

Generally high shrinkage is associated with high densities. The size and shape of the wood piece can influence the shrinkage, as can the degree of drying, which can affect the shrinkage for some wood species [53]. With moisture variation, the relationship between moisture content and shrinkage is not linear, but overall, shrinkage decreases as moisture content increases. Above the FPL, no wood undergoes dimensional deformation, so it is clear that *Mimusops andongensis* can withstand the wet environment although its mechanical characteristics will decrease if it is completely wet. Referring to the study of Obataya *et al.* [50] on *Picaea sitchensis*, its use in a humid environment could generate, in the critical case, a loss of mechanical characteristics, in particular, of the modulus of elasticity of only 15 to 20 %. In this range of loss of mechanical characteristics, the average modulus of elasticity would be in equal variation between 14, 776 and 15, 700 MPa bringing the *Mimusops andongensis* pile in the woods of medium modulus (MOE < 15,000 MPa) or heavy modulus (MOE > 15,000 MPa) [27]. Such characteristics, cumulated with the other characteristics in the same range of variation in a situation of humidity or shrinkage-swelling would be limited [53], *Mimusops andongensis* would make a species very appreciated in terrestrial constructions as in situations of high stress as in wetlands, lacustrine or in contact with water. Its natural habitat of wetlands and riparian forest [15] would be of these assets.

It is to be hoped that following this work, studies of natural durability, behaviour at different moisture contents, thermal behaviour and behaviour in the face of mineral salts specific to our aquatic and marine environments will be carried out to confirm its average shrinkage, its high modulus and its character as a heavy or even very heavy wood due to its density.

CONCLUSIONS

The study of the physico-mechanical and acoustic characteristics of *Mimusops andongensis* with respect to the characteristics of prized species or woods of high technological value in Benin such as Tali, African Ebony, *Cylicodiscus gabunensis, Anogeissus leiocarpus, Manilkara multinervis* reveals its high potential because of its high technological characteristics.

Mimusops andongensis wood, previously unknown technologically, is a heavy wood with high modulus and low tangential shrinkage, volume shrinkage and radial shrinkage overall. This wood has low shrinkage anisotropy with a high mechanical stiffness for a very low vibration energy dissipation. It is a heavy or even very heavy wood due to its density which even in a humid environment would have a maximum loss of 20%. Such a loss would still guarantee good technological properties. These properties of *Mimusops andongensis* show its good potential in structural works in both dry and wet environments. It is to be wished studies of durability, thermal behaviour and preservation treatment to complete its technological characteristics. It would also be advisable to further explore the ecology and silviculture of the species to work on its domestication as a guarantee of a planned multifunctional *Mimusops andongensis.*

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